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TRANSLATION

ATOMIC ENERGY AND AVIATION (CHAPTER VII)

By

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

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ATOMIC ENERGY AND AVIATION (CHAPTER VII)

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CHAPTER VII

ATOMIC ENERGY AND AVIATION

Literally before the eyes of our generation there has been accomplished a gigantic jump forward in development of aviation. Only some 50—60 years ago, the flying range of aircraft was measured in tens of meters, and weight of payload in kilograms. And now aircraft accomplish non-stop flights for 10—12 thousands of km and contain 150—200 passengers. Speed of contemporary transports aircraft has approached close to speed of sound, reaching 900—1000 km/hr. The order of the day is construction of aircraft of still larger dimensions. All this is connected with increase of power of the power plant of aircraft and weight of fuel transported by them. Already at present the weight of payload constitutes only 25% of the gross weight; it is a few times less than the weight of the reserve of fuel transported by the aircraft.

Power of power plants of contemporary big aircraft has reached 60 thousand horsepower and more.

Increase of speed and flying range of aircraft will cause a still larger increase of power of their power plants.

It is not surprising that in connection with this there appears great interest toward problem of use of atomic energy for air transport.

However, in order to correctly estimate prospects of development of atomic aircraft power plants, it is necessary to consider the main directions of further possible development of aviation technology.

Possibility of increase of speed of flight should be considered in conformance with the purpose of the aircraft.

Thus, for instance, it is doubtful whether it is necessary and expedient to use aircraft with supersonic speed of flight for local or intraregional transport. For short distances between points of flight, total saving of time of delivery due to increase of speed of flight is insignificant and cannot justify the inevitable increase of expenses. It is another matter when we speak about intercontinental or round-the-world routes. In this case saving of time due to speeding up of flight may be significant, and the maximum attainable speed of flight for aircraft with such a purpose will be determined in practice by technical possibilities.

At present, for quite large distances there are used aircraft with transonic speeds of flight: 850—950 km/hr. In technology it has been agreed to designate speed of flight by mach number M.* Thus, speed of flight can be expressed not only in number of kilometers per hour, but also by mach number M (for instance, 2.5 M = 2700 km/hr). How great may be the speed of flight of aircraft? Already at present special aircraft attain a speed of flight equal to 6 M.

Under present conditions this flight is record-breaking. However, from history of technology and, in particular, from history of development of aviation, we know that today's record becomes tomorrow's normal operating conditions. Achievement of such a huge speed

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*Mach number M in gas dynamics and high speed aerodynamics is the dimensionless ratio of speed of flight to speed of sound. Thus, in the case of m = 2 to 3, speed of flight is 2—3 times the speed of sound.

requires surmounting of a number of difficulties. Main difficulty is that during great speed of flight of aircraft in dense layers of atmosphere, due to friction against the air, the skin and all units and structural elements of the aircraft adjacent to it are heated. For this reason meteorites entering the atmosphere burn and artificial satellites cease their existence when they with time descend into the lower, dense layers of the atmosphere. The struggle with overheating of skin of aircraft is carried on in several ways. Thus, the external surface can be covered with thermally insulating materials, which have poor thermal conductivity, or artificially cooled. It is possible

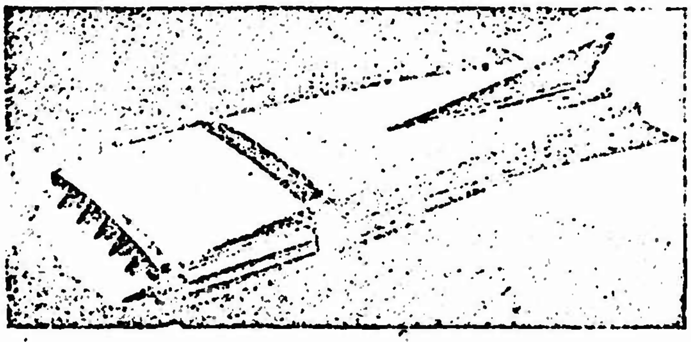

Fig. 20. An aircraft of the future.

also in the construction of the aircraft to apply heat-resistant metals. However, the most effective way is flight in upper layers of atmosphere at altitude of 30—40 and more kilometers from surface of earth, where air density is insignificantly low. Such a solution is also advantageous because at an altitude of 30—40 km, an aircraft in rarefied atmosphere experiences significantly lower resistance to its motion, and consequently can fly with high speed with the same or lower power of power plant. For flight at such high altitudes, only jet aircraft are useful, since creation of the necessary thrust with the help of a propeller in rarefied atmosphere is impossible.

Furthermore, at high speeds of flight efficiency of propeller is lowered sharply.

With what speed and when will aircraft fly at such great altitude? This question is so far impossible to answer exactly, inasmuch as for achievement of this goal there is necessary much research and experiment, anticipation and prediction of the course of which is difficult. It is possible, for instance, to assume that in the next 10 years the speed of transport aircraft will reach 2—3 M. However, this is not the limit. Already now there is being conducted research for the purpose of determination of conditions of flight with speed of 15—20 M. This means that circling of globe along the equator will take 2—2.5 hour, and flight from Moscow to New York will take about 1 hour. These speeds of flight at first glance are apparently fantastic, but in reality they are fully realizable, although only in the more distant prospects of development of air transport. With further increase of speed of flight, due to great compression of air in zone of flying aircraft, there significantly are improved conditions of operation of motors. Therefore, for supersonic aircraft (at speed of 2.5 M and above), specific consumption of fuel decreases by 2 times, and weight of power plant--by 10—30 times as compared to an aircraft flying at subsonic speeds. One of serious problems of use of supersonic speeds is the characteristic high landing speed. It turns out that this difficulty also can be surmounted, if by compression of air there is created under the wings an air cushion. Experiments and calculations show that due to this landing speed may be decreased almost by twice.

There are also other ways of effective use of supersonic aircraft. We will imagine a very large aircraft containing 500—1000 passengers continuously for several months of flying at supersonic

speed at a great altitude over a closed route. Such an aircraft is very profitable for a number of reasons: there decreases the risk of its operation connected with frequent landings, there is increased the efficiency of its use. Since power required at the moment of takeoff significantly exceeds power necessary for horizontal flight, a large part of its motors for a prolonged time will be in reserve and can be repaired without harm for operation of aircraft.

But how can there be carried out landing and debarkation of passengers? This operation can be carried out with the help of local aircraft which have smaller dimensions. Such interceptor aircraft take off when the transcontinental aircraft approaches. Then speeds of the aircraft are equalized and they safely come into contact. Through special hatches there is carried out exchange of passengers, the transcontinental aircraft flies away further, and the local aircraft lands the arriving passengers at the airport.

There may be proposed another variant: non-stop flight is carried out by a towing aircraft, which is radio-controlled and accomplishes trips in a determined direction with constant supersonic speed. When necessary to this towing craft there are attached local aircraft, which accomplish with the help of their own turbines only takeoff.

There exists the idea of an aircraft which has, instead of wings inside the fuselage, guide plates before the jet turbines.

Air sucked by compressors of jet turbines initially passes through these plates and creates a lift force. It is interesting that, when set at the appropriate angle to the horizontal plane, these plates can lift a horizontal aircraft vertically upwards. Then, at the desired altitude, by changing the angle of the plates, it is possible to give aircraft the direction of horizontal flight.

Of great interest also is the idea of engineless flight of aircraft, which was proposed by the noted scientists, Zenger and Bredt, for use as with transcontinental aircraft. Everyone, surely, must have seen how a flat stone jumps, skipping from the water. Cast flatways by a skilled hand, such a stone can accomplish 5—10 jumps.

The idea of engineless flight is similar to this entertaining effect. With the help of a jet catapult and a rocket motor, such an aircraft rises to an altitude of 150 km, attaining of speed of about 22 thousand km/hr. Further, engineless flight of aircraft will occur along a ballistic curve until the aircraft descends into dense layers of atmosphere. We will imagine that on the aircraft, lifted to an altitude of 150—200 km, the turbines are turned off and it starts to glide downwards along a flat curve in a given direction. Speed thus will increase according to acceleration due to gravity (9.81 m/sec^2) and by the moment of approach to the dense layers of atmosphere becomes very great. Upon encounter of lower plane of fuselage of aircraft with dense layers of atmosphere, there will be formed a lift, under action of which aircraft by inertia again rises to a high altitude. Naturally after ever such "jump" the altitude of climb of aircraft will decrease; however, total flying range due to all such jumps can reach 25—30 thousand km, i.e., can approach the distance of a round-the-world flight. It is calculated that speed of flight of such an aircraft will be near 16 thousand km/hr ($M \cong 15$). Thus, a round-the-world flight will continue for a little more than two hours. It is interesting to note that with such high flight speed, the landing speed of the aircraft is small--only about 150—170 km/hr (Fig. 21).

Takeoff and initial boost of such an aircraft to initial altitude may be performed by a special towing aircraft; when flight

continues by gliding. In this case, on the actual airliner the power plant may be of a reserve nature.

Such in broad terms are the prospects and directions of development of air transport.

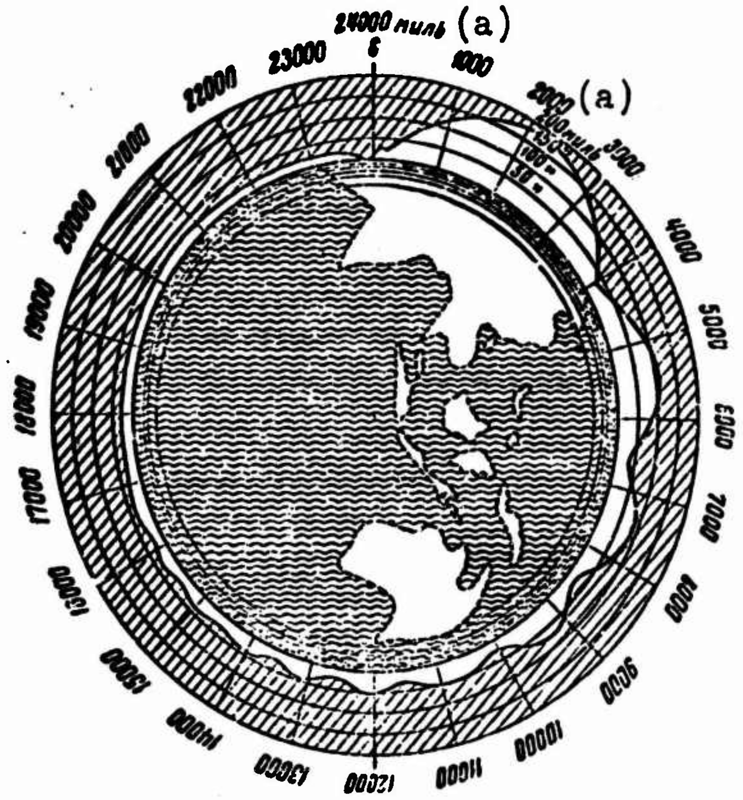

Fig. 21. Orbital aircraft for round-the-world cruising.
KEY: (a) miles.

It is clear that for air transport of high speeds and long flying range there will be demanded a power plant of huge power, measured in tens and hundreds of thousands of horsepower.

From this point of view, use of atomic energy for power plants of aircraft presents exceptional interest.

In what state is this problem? With what problems was it necessary for scientists and engineers to meet on this path? What are the prospects of its solution? Here are questions which inevitably must appear. We will endeavor to answer them.

Basic difficulty appearing in attempt to create aircraft with atomic power plants is the limitation of weights and dimensions.

Even a very big contemporary aircraft has gross weight of 100—120 tons. Here is included the weight of aircraft and power plant (35—45%), reserves of fuel (35—40%) and payload (20—25%). Thus, acceptable weight of reactor and biological shield of power plant with power of 60—80 thousand horsepower should be not more than 50—60 tons. Difficulty of this problem can be distinctly imagined if for comparison we will remember that even the weight of an atomic power plant (i.e., also transport installation) of power will be 1.5—2.5 thousand tons.

Severe limitations are caused by dimensions of airplane fuselage, which has length of 40—45 m and height of 4—5 m. Reactor of contemporary type with all mechanisms and equipment belonging to it will occupy almost the whole internal volume of an aircraft.

Dimensions of reactor can be decreased if we use fuel with higher content of uranium 235. However, even in this case a significant part of fuselage will be occupied by reactor equipment. Solution of this problem in practices obviously, will go either in the way of decrease of dimensions and weight of reactor, or in the way of increase of gross weight of aircraft. One may assume that for aircraft with atomic power plants, gross weight of 400—500 tons is optimium. Such an aircraft can contain several hundred men, payload weight of it is 100—150 tons.

No less complicated is the problem of protection of reactor equipment. It should be borne in mind that accidents and destruction of reactor during flight of aircraft at a high altitude can lead to radioactive contamination of a huge region. Obviously, flights of

aircraft with atomic power plants above large inhabited localities would be forbidden.

Reactor shielding should not only protect passengers and aircrew from radioactive emissions, but also prevent possibility of scattering and contamination by radioactive products of a more or less large region in case of crash of aircraft. For this, equipment of primary loop of an aircraft atomic power plant should be, apparently, inclosed in container significantly more durable than those which are used on atomic vessels.

In principle schemes of atomic power plants do not differ from considered schemes of ship atomic power plants. However, up to now there still has not been published one design of an aircraft atomic engine, in spite of the fact that research in this direction has been conducted already for more than 10 years.

Nonetheless, design-research on creation of atomic aircraft are being conducted in this direction very intensely. Thus, in particular, already in 1956 an aircraft took off on board which there was an operating reactor with power of 1000 kilowatts, weight of 20 tons; however, it was only as a load. Purpose of experiment was study of stability of operation of reactor under conditions of flight.

Inasmuch as on supersonic aircraft there are installed turbojet engines, a reactor should be designed for operation at very high temperatures, an the order of 1000° and above.

Before we consider specific designs we will meet with general properties and characteristics of reactors of propulsion systems for aircraft.

Aircraft Reactors

At present, development of technology is at a stage when

advancements in development of new chemical fuels asymptotically approaches its maximum limit. This limit is connected with the fact that a relatively small reserve of energy, is concentrated in a unit of weight of chemical fuel.

Now, when this limit has practically been attained, providing for development of aircraft in direction of increase of their payload capacity, speed and flying range is connected with an extraordinarily large reserve of fuel which has to be taken on board the aircraft.

Technically realizable dimensions and weight of aircraft, for instance, limit the payload capacity, and at the same time range and speed.

Scientists have calculated that for realization of certain interplanetary flights, a chemical fuel rocket is required to consist of 99% fuel by weight. Obviously, such a rocket is impossible to construct.

For these reasons, as soon as there was proven possibility of practical use of nuclear energy, scientists and designers working in region of aviation and aircraft turned to this new source of energy.

Although investigations in this region have been conducted relatively recently, now it is already possible to speak about certain peculiarities of aircraft reactors, and about those requirements which they have to meet.

First of all this is high power provided by the power plant. In aircraft and rocket nuclear engines magnitude of thermal power is measured in hundreds of thousands of horsepower.

Another important index is the dimensions and weight of reactor. Since we always attempt to obtain high power at minimum weight, these two indices can be combined and the reactor can be evaluated by its

specific weight (number of kilograms of weight necessary for obtaining one unit of power), which should be as small as possible.

Reliability and radiation safety of reactor and installation on the whole are the main operational requirements.

Technical and operational requirements almost always contradict each other, since the first give high temperatures and minimum weight (thickness of construction), i.e., which lower strength of material and, hence, reliability. Nonetheless the attempt is to make all aircraft reactors high-temperature reactors (700°—3000° C) in order to increase efficiency and decrease dimensions of the installation. Creation of high-temperature reactor is connected with a number of problems: in the first place with the problem of materials.

A specific peculiarity of all reactors, including aircraft reactors, is the presence of harmful neutron and gamma radiation, as a consequence of which it is necessary to provide special protective shields. Inasmuch as the attempt is to obtain minimum dimensions, in reactors of aircraft engine installations there is used nuclear fuel with large content of uranium 235 (content of uranium 235 in fuel reaches sometimes 90%). By this is due also to the fact that almost all reactors intended for aircraft installations have liquid-metal cooling, since liquid metal removes heat best of all. Use in these reactors of water and organic heat-transfer agents is impossible, inasmuch as they do not permit high temperatures, and for circulating gaseous heat-transfer agents there are required high pressures and capacities.

Aircraft nuclear power plants

A contemporary turbojet passenger aircraft with weight of 100—1200 tons flying with speed near 800 km/hr requires about 15—20

tons of fuel for one hour of flight.

It is known that increase of power of motor is proportional to third power of increase of speed. Therefore an aircraft flying with speed of 2400 km/hr will expend about 150—180 tons of fuel per hour.

From this point of view the use of atomic energy for power plants of aircraft presents exceptional interest. Motors which can be applied in this case do not differ (besides source of energy) from motors operating on chemical fuel. Possible types of motors are turbojet, turboprop and ramjet.

In these motors the usual combustion chamber is replaced either by a reactor or by a heat exchanger. In the first case we have a direct scheme in the second--an indirect scheme of heating of the mass carrier. Diagrams of motors are given in Fig. 22.

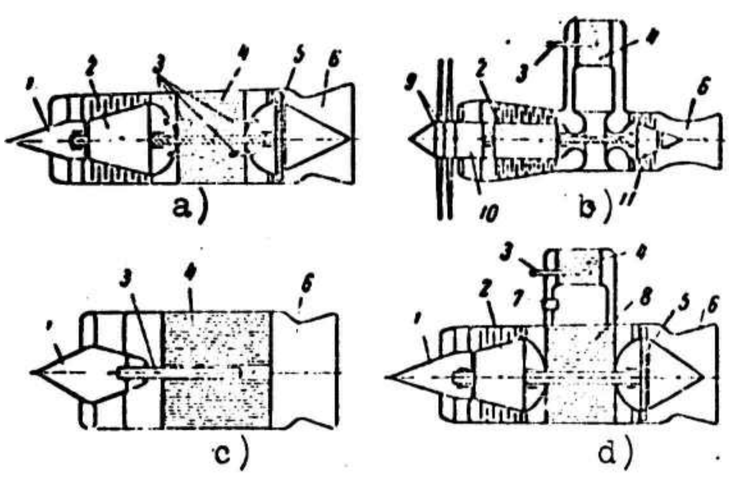

Fig. 22. Diagrams of aircraft atomic engines. a) turbojet engine (TRD); b) turboprop engine (TVD); c) ramjet engine (PVRD); d) closed cycle turbojet engine.
1) inlet cone; 2) compressor; 3) control rod; 4) reactor; 5) turbine; 6) jet nozzle; 7) pump; 8) heat exchanges; 9) propellors; 10) reductor; 11) air turbine.

Direct heating system (or, as it is called, open cycle system)

is simpler, but has its own deficiencies: 1) it is limited with respect to temperature (since atmospheric air serving as a mass carrier is a strong oxidizer); 2) large dimensions of reactor (inasmuch as air is a bad heat-transfer agent); 3) air ejected by motor is radioactive and contaminates the atmosphere.

Advantage of indirect heating system (closed cycle) is that it is possible to select the most effective heat-transfer agent and, furthermore, to eliminate radioactive area contamination.* Deficiency of the system is a certain complication of it due to additional introduction of a heat exchanger, pump and coolant loop. Moreover temperature somewhat drops during transmission of heat from heat-transfer agent to tube of heat exchanger. The most effective heat-transfer agent in closed cycle is liquid metal. Gaseous heat-transfer agent has somewhat worse characteristics in view of necessity of large pressure in the loop and large losses of pressure.

We will consider what characteristics and parameters are specifically connected with aircraft nuclear engines. It is necessary immediately to explain that at present there is not yet one operational nuclear aircraft engine. Therefore, figures presented below are based on published data pertaining either to designs or to experimental models.

Nuclear Open Cycle TRD

Turbojet engine works according to the following principle:

Atmospheric air with speed equal to speed of flight of aircraft enters intake device of motor, where it is decelerated. During deceleration temperature and air pressure are increased to approximately

*Reactor of closed cycle engine may be made with significantly smaller dimensions in comparison with open cycle reactor. This will allow sharp decrease of weight of biological shield.

50°—250° C and 1—3 atm respectively. Then air is compressed in compressor (pressure of it is increased by 5—7 times) and enters the reactor. Passing through channels of reactor, it is heated to temperature of 800—1100° C and enters the turbine which rotates the compressor, and then with great speed passes through the nozzle, creating reactive thrust.

In order to obtain a reactor with minimum dimensions, it is necessary to heat the mass carrier (air) to maximum possible temperature. It is necessary thus to consider that air is a heat-transfer agent; therefore temperature of walls of reactor should be 100—200° C higher than temperature of heat-transfer agent. Inasmuch as wall temperature of reactor is limited by properties of its materials, maximum temperature of air also is limited.

For obtaining of thrust comparable with thrust of motor operating on chemical fuel (nearly 10 tons), at the attained level of temperatures nuclear reactor should have diameter of 1.5—2 m, length 1—1.5 m, and develop thermal power reaching 300—400 megawatts.

Fuel material in such a reactor can be high-temperature uranium compounds, for instance uranium dioxide. For increase of heat transfer surface fuel either is homogeneously mixed in moderator or is located along channels contained in it. As moderator can be used high-temperature materials--beryllium oxide, graphite and certain others. Structural materials have to possess good stability to oxidation at high temperatures.

The scheme of direct air cycle can be used also with turboprop and ramjet engines.

Ramjet Atomic Engine (PVRD)

The usual ramjet engine operating on chemical fuel is intended

for installation on supersonic aircraft or rockets. Compression of mass carrier which is necessary for any engine in this engine is produced due to deceleration of flow of air which is incident with supersonic speed. Such a motor is not able to develop thrust while stationary; therefore, for takeoff of aircraft with such a motor there is necessary an additional launching arrangement.

Let us consider the design of a nuclear ramjet engine for a guided missile moving with speed of nearly 3200 km/hr (see Fig. 22c). Air captured by motor is heated in reactor to temperature of the order of 1000° C and then is ejected through the nozzle, creating reactive thrust. Heat output of such a reactor is approximately 150 Mw; diameter and length are 1.8 m. In a reactor of homogeneous type are arranged longitudinal channels, through which passes air (they occupy approximately half of frontal surface of reactor). Temperature of wall of channel is somewhat higher than 1200° C. At a speed of 3 M, altitude of flight of 20,000 m and temperature of air at the outlet of the reactor of around 1000° C, the motor will develop thrust of up to 6 tons. This will allow us to create a missile with total weight of 24 tons. Payload in this case will be nearly 6 tons. If it is possible to increase temperature of air at outlet of reactor to 1200° C, then thrust will be increased to 8 tons, weight to missile to 32 tons, and payload—to 12 tons. As for a motor operating by direct cycle, basic problem is selection of structural materials which are stable to oxidation. Such systems are planned to be pilotless; therefore questions of biological shielding here are less complicated. Both turbojet and ramjet engines can be made also with a closed cycle scheme.

Closed Cycle System

Above we have already briefly discussed advantages of closed cycle scheme. Basic advantage is the possibility of creation of a small-size reactor. By applying liquid-metal coolant, which removes heat very well, it is possible to significantly reduce the heat transfer surface of the reactor. This, in turn, will allow us to cfeate a small-size reactor in which there is absent a moderator. Although such (fast neutrons) reactors require large quantity of fuel, they give us the possibility to lower sharply weight of biological shield, and this means, of the entire power plant.

As for any other high-temperature reactor, basic problem remains the problem of selection of structural materials. Special difficulties appear in case of use of liquid metals, which cause strong corrosion of structural materials.

Closed cycle scheme differs from the above-considered schemes in the fact that mass carrier heated in reactor enters a special heat exchanger. Reactor and heat exchange are connected by a closed loop, in which liquid or gas circulates, thereby transfering heat from reactor to heat exchanger. There is possible also application of a two-loop installation with intermediate neat exchanger, which is convenient for the reason that the first loop, which has small dimensions may be fully shielded. Furthermore, it is difficult to select material of heat exchanger so that it is simultaneously stable to oxidation and to corrosion in a liquid metal medium.

As structural materials of closed cycle reactors are used refractory metals (niobium, molybdenum, tungsten), and also certain refractory alloys.

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